

Quark Correlations Inside Hadrons And Single Diffraction

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Abstract

Hadron structure is considered in the frame of Strongly Correlated Quark Model (SCQM). It is shown that quark correlations result in fluctuations of hadronic matter distributions and single diffractive dissociation processes in hadronic collisions, hard or soft, are manifestation of these fluctuations inside colliding hadrons.

1 Introduction

Elastic and inelastic pp and $\bar{p}p$ –interactions play an important role in understanding of structure of hadrons. Variety of scattering processes, differentiation them into hard and soft ones, single and double diffraction and central hadron production tell us that this structure is rather complicated. What is the source of complexity? If hard processes are the area of application of current quark consideration then soft ones are described in constituent quark approach. Interplay between hard and soft interactions in high energy experiments strictly relates to interconnection between small and large size quark configurations inside a hadron. We think that this interplay is a manifestation of fluctuations of hadronic matter distributions inside hadrons and these fluctuations in turn are results of correlated motion of valence quarks inside hadrons.

The question arises: is it possible to construct the dynamical system of quarks which can be observed at one instant of time as constituent (dressed) quarks and at the another one - as current (bare) quarks? Proposed by author the semiclassical model of strongly correlated quarks, SCQM, demonstrated how these configurations could be realized inside hadrons[1]. In this paper we give further elaboration of the model which possesses the features of both constituent and current quark models and allows one to extract confining potential and force(Section 2). In Section 3 we apply this model for description of diffractive processes and show that explicit manifestation of quark correlation inside hadrons is a single diffractive scattering.

2 Strongly Correlated Quark Model

Let us imagine the following hypothetical picture: single, colored quark imbedded into vacuum. Because of vacuum fluctuations one can observe two competing processes: first, polarization of $\bar{q}q$ sea by the color field of valence quark (VQ) and second, the tend of vacuum fluctuations to destroy this polarization. As a result, one can say about a vacuum pressure on a single, colored quark. This effect can be interpreted as the "response" of the vacuum on the presence of, say, point defect or dislocation like in solid state physics. What happens if we place in vicinity of this quark the corresponding antiquark? By virtue of opposite color signs their polarization fields interfere in the overlapping region **destructively**. So the pressure of vacuum on quark (antiquark) from outside exceeds that one going from inner space between quark and antiquark. This results in an **attractive** force between quark (dislocation) and antiquark (antidislocation). The density of the remaining part of polarization field around quark (antiquark) is identified with hadronic matter distribution. At maximum displacement in $\bar{q}q$ - system, that corresponds to small overlapping of polarization fields, hadronic matter distributions have maximum values. So quark and antiquark located nearby start moving towards each other. The closer they to one another, the larger destructive interference effect and the smaller hadronic matter distributions are around VQs and the larger their kinetic energies.

For such interacting $\bar{q}q$ - system the total Hamiltonian is

$$H = \frac{m_{\bar{q}}}{(1 - \beta^2)^{1/2}} + \frac{m_q}{(1 - \beta^2)^{1/2}} + V_{\bar{q}q}(2x), \quad (1)$$

were $m_{\bar{q}}$, m_q – masses of valence antiquark and quark, $\beta = \beta(x)$ – their velocity depending on displacement x and $V_{\bar{q}q}$ – quark–antiquark potential energy with separation $2x$. It can be rewritten as

$$H = \left[\frac{m_{\bar{q}}}{(1 - \beta^2)^{1/2}} + U(x) \right] + \left[\frac{m_q}{(1 - \beta^2)^{1/2}} + U(x) \right] = H_{\bar{q}} + H_q, \quad (2)$$

were $U(x) = \frac{1}{2}V_{\bar{q}q}(2x)$ is potenial energy of quark or antiquark. Therefore, keeping in mind that quark and antiquark are strongly correlated we consider each of them separately as undergoing oscillatory motion in 1+1 dimension. Generalization to three–quark system in baryons is performed according to $SU(3)_{color}$ symmetry: an antiquark is replaced by two correspondingly colored quarks to get color singlet baryon and destructive interference takes place between color fields of three valence quarks. Putting aside the mass and charge differences of valence quarks we may say that inside baryon three quarks oscillate along the bisectors of equilateral triangle. Hereinafter we consider that axis Z is perpendicular to the plane of oscillation XY .

VQ with its polarized surroundings (hadronic matter distribution) form constituent quark. According to our approach potential energy of valence quark, $U(x)$, corresponds to the mass M_Q of constituent quark:

$$U(x) = \text{const} \int_{-\infty}^{\infty} dz' \int_{-\infty}^{\infty} dy' \int_{-x}^{\infty} dx' \rho(x, \mathbf{r}') \approx M_Q(x) \quad (3)$$

with

$$\rho(x, \mathbf{r}') = |\varphi(x, \mathbf{r}')|^2 = \left| \varphi_Q(x' + x, y', z') - \varphi_{\bar{Q}}(x' - x, y', z') \right|^2. \quad (4)$$

The knowledge of the mechanism and structure of vacuum polarization around valence quark would give the information about the confining potential. We cannot say at the moment for sure what is the microscopical mechanism of interaction of valence quark with vacuum. It could be instanton induced interactions, excitation of fractal structure of space-time, etc. So we assume, as a first approximation, that the polarization field can be taken in gaussian form:

$$\varphi_Q(\mathbf{r}) = \varphi_Q(x, y, z) = \varphi_Q(x_1, x_2, x_3) = \frac{(\det \hat{A})^{1/2}}{(\pi)^{3/2}} \exp\left(-\mathbf{X}^T \hat{A} \mathbf{X}\right), \quad (5)$$

where exponent is written in quadratic form. The same is for $\varphi_{\bar{Q}}(\mathbf{r})$. We define the mass of constituent quark at maximum displacement

$$M_{Q(\bar{Q})}(x_{\max}) = \frac{1}{3} \left(\frac{m_{\Delta} + m_N}{2} \right) \approx 360 \text{ MeV}, \quad (6)$$

where m_{Δ} and m_N are masses delta-isobar and nucleon correspondingly. Therefore, the parameters of the model are the masses of VQs, $m_{q(\bar{q})}$, which are chosen to be 5 MeV, maximum displacement, x_{\max} , and parameters of gaussian function, $\sigma_{x,y,z}$. As shown below, x_{\max} and $\sigma_{x,y,z}$ are adjusted by comparison of calculated and experimental values of inelastic cross sections, $\sigma_{in}(s)$, for pp and $\bar{p}p$ - collisions. Using (3)–(5) we can calculate the confining potential $U(x)$ and force $F(x) = -\frac{dU}{dx}$. They are shown in Fig. 1. As one can see the confining potential is essentially nonlinear. The behavior of potential evidently demonstrates the relationship between constituent and current quark states inside a hadron. At maximum displacement quark is nonrelativistic, constituent one (VQ surrounded by "polarized sea"), since according to (3) the confining potential corresponds to the mass of constituent quark. At the origin of oscillation, $x = 0$, antiquark-quark in mesons and 3 quarks in baryons, being close to each other, have maximum kinetic energy and correspondingly minimum potential energy and mass: they are relativistic, current quarks (bare VQs). Intermediate region corresponds to increasing (decreasing) of quark's mass by dressing (undressing) of quarks due to vacuum polarization. This mechanism agrees with local gauge invariance principle. Indeed, phase rotation of wave function of single quark in color space ψ_c on angle θ depending on displacement x of the quark in coordinate space

$$\psi_c(x) \rightarrow e^{i\theta(x)} \psi_c(x) \quad (7)$$

results in it's dressing (undressing) by quark and gluon condensate that corresponds to the transformation of gauge field $A_{\mu} = (\varphi, 0, 0, 0)$

$$A_{\mu}(x) \rightarrow A_{\mu}(x) + \partial_{\mu}\theta(x). \quad (8)$$

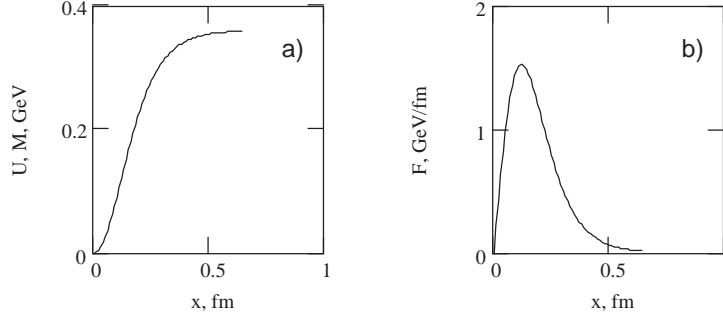


Figure 1: a) Potential energy of valence quark and mass of constituent quark; b) "Confinement" force.

Here we dropped color indices and took into account only scalar component, φ , of gauge field. Thus gauge transformation maps internal (isotopic) space of colored quark onto coordinate space. On the other hand this dynamical picture of VQ dressing (undressing) corresponds to chiral symmetry breaking (restoration). The behaviour of field φ and hadronic matter distribution, ρ , for quark-antiquark system during their oscillations is shown in Fig. 2. Due to this mechanism of VQs oscillations nucleon runs over the states corresponding to the certain terms of the infinite series of Fock space

$$|B\rangle = c_1 |q_1 q_2 q_3\rangle + c_2 |q_1 q_2 q_3 \bar{q} q\rangle + \dots \quad (9)$$

Confining force drastically differs from the one given by string models. When VQs are close each other it is very weak and fulfills the "asymptotic freedom" behavior of quarks of QCD. At larger distances between VQs it starts growing rapidly, then reaching maximum value goes down, asymptotically approaching zero. Thus at large distances inside hadrons quarks being in a constituent state are almost free. Hence, it is clear why additive quark model, where quarks are treated as massive, almost unbound and extended objects, works well. We must emphasize that interaction between VQs is not direct but a result of polarization of surrounding vacuum combined with destructive interference. Attractive force between VQs in ground state hadrons does not appear as gluon string but goes from vacuum suppression that predominates from outside. Therefore, our approach reflects the features of bag models, as well. The model is in agreement with the experiments (Fig. 3) for description of VQ structure function inside a

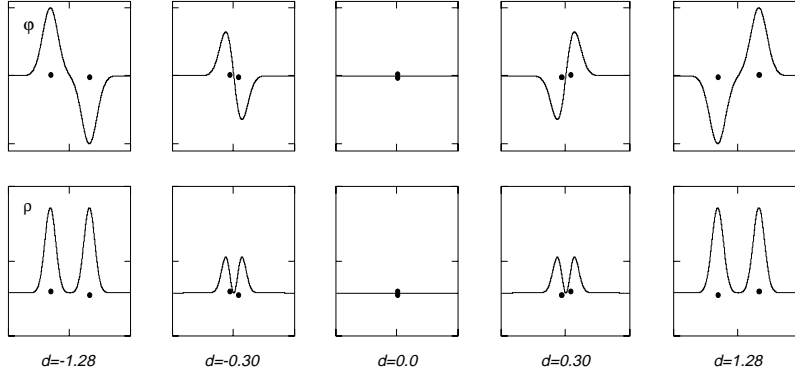


Figure 2: Evolution of field φ , (Eq. (5)), and hadronic matter distribution ρ , (Eq. (4)), in quark-antiquark system during one-half of the period of oscillations; $d = 2x$ - distance in *fermi* between quark and antiquark depicted as dots.

nucleon

$$F_2^{ep} - F_2^{en} = \frac{x_F}{3} [u_v(x_F) - d_v(x_F)]. \quad (10)$$

Of course, our description is classical and we must take into account quantum corrections. It will be the subject of forthcoming papers. Nevertheless, classical consideration of VQ oscillations is justified by E. Schrodinger's paper[2] where he, analyzing the motion of wave packet solution of time dependent Schrodinger equation for harmonic oscillator, demonstrated that this wave packet moves in exactly the same way as corresponding classical oscillator. In our model VQ with its surroundings can be treated as (nonlinear) wave packet. In forthcoming paper we'll show that these wave packets possess soliton-like features.

3 Application to Diffractive Processes

Different configurations of quark contents in colliding hadrons realized at the instant of collision result in different types of reactions. The probability of finding any quark configuration inside a hadron is defined by the probability of VQ's displacement in proper frame of a hadron:

$$P(x)dx = \frac{Adx}{\sqrt{1 - m_q^2/(E - V)^2}} \quad (11)$$

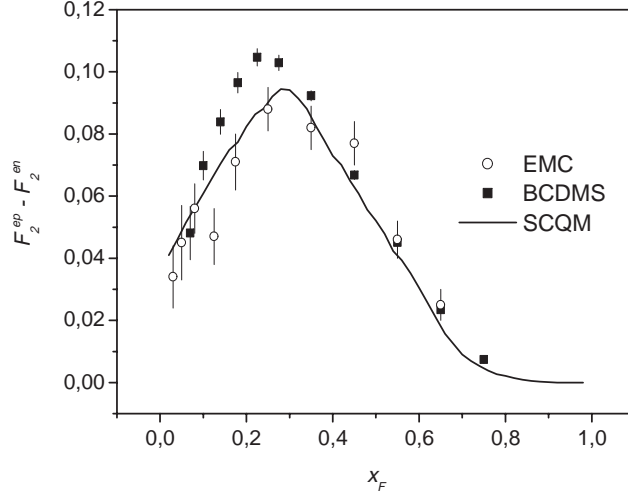


Figure 3: Valence quark structure functions in nucleons; data point are from papers[5, 6].

with

$$\int P(x)dx = 1. \quad (12)$$

Configurations with nonrelativistic constituent quarks ($x \simeq x_{max}$) in both colliding hadrons lead to multiparticle production in central and fragmentation regions. Hard scattering with jet production and large angle elastic scattering take place when configurations with current VQs ($x \simeq 0$) in both colliding hadrons are realized. Intermediate configurations inside one (both) of colliding hadron are responsible for single (double) diffraction processes and semihard scattering. Using impact parameter representation, namely Inelastic Overlap Function (IOF), we can calculate total, inelastic, elastic and single diffractive cross sections for pp and $\bar{p}p$ collisions. In impact parameter representation IOF can be specified via the unitarity equation

$$2Imf(s, b) = |f(s, b)|^2 + G_{in}(s, b), \quad (13)$$

where $f(s, b)$ —elastic scattering amplitude and $G_{in}(s, b)$ is IOF. IOF is connected with inelastic differential cross sections in impact parameter space:

$$\frac{1}{\pi}(d\sigma_{in}/db^2) = G_{in}(s, b). \quad (14)$$

Then inelastic, elastic and total cross sections can be expressed via IOF as

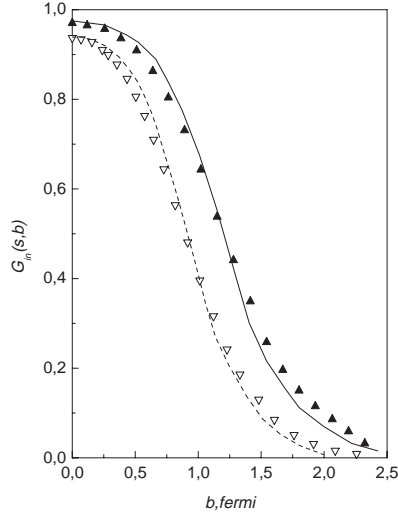


Figure 4: Inelastic overlap function for pp and $\bar{p}p$ - collisions at $\sqrt{s} = 53$ and 540 GeV ; triangles are Henzi and Valin approximation[3].

$$\sigma_{in}(s) = \int G_{in}(s, \mathbf{b}) d^2 \mathbf{b}, \quad (15)$$

$$\sigma_{el}(s) = \int \left[1 - \sqrt{1 - G_{in}(s, \mathbf{b})} \right]^2 d^2 \mathbf{b}, \quad (16)$$

$$\sigma_{tot}(s) = 2 \int \left[1 - \sqrt{1 - G_{in}(s, \mathbf{b})} \right] d^2 \mathbf{b}. \quad (17)$$

Since IOF relates to the probability of inelastic interaction at given impact parameter, (12), we carried out Monte Carlo simulation of inelastic nucleon-nucleon interactions. Inelastic interaction takes place at definite impact parameter b if at least one pion is produced in the region where hadronic matter distributions of colliding protons overlap

$$4M_{q_i} \gamma_{q_i} M_{p_j} \gamma_{p_j} \int \rho_{q_i}(\mathbf{r}) \rho_{p_j}(\mathbf{r} - \mathbf{r}') d^3 \mathbf{r} \geq m_{\pi_{\perp}}^2, \quad (18)$$

where indices q_i and p_j refer to quarks from different nucleons and $i, j = 1, 2, 3$, M_{q_i} , M_{p_j} – masses of hadronic matter composed in constituent quarks q_i and p_j , γ_{q_i} , γ_{p_j} – their γ -factors; integrand expression is convolution of hadronic matter density distributions of quarks q_i and p_j . This condition corresponds Heisenberg picture[4] with modified right hand side: m_{π}^2 in the original Heisenberg inequality is replaced by $m_{\pi_{\perp}}^2$. It is justified by the fact that the average

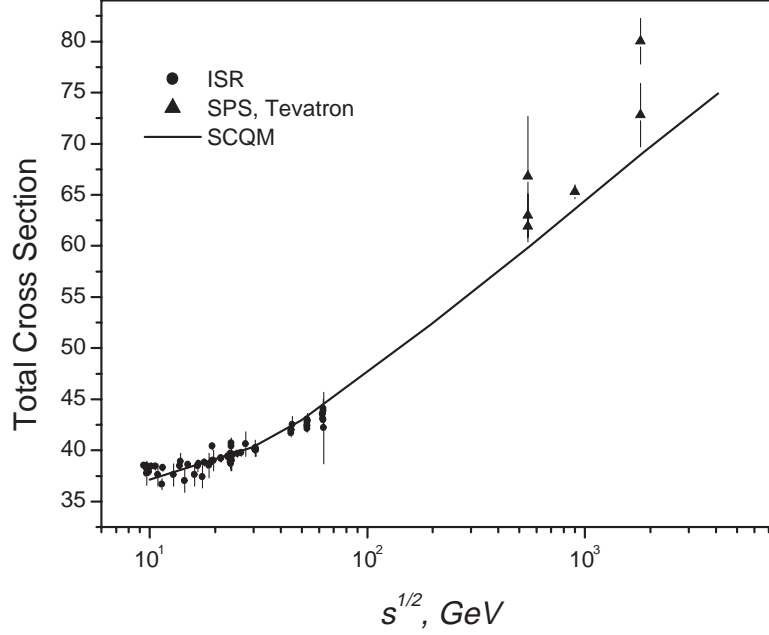


Figure 5: Total cross section for pp and $\bar{p}p$ collisions; data points are compilations of experimental data taken from electronic data base HEPDATA[11].

transverse momentum of produced particles increases with energy. Specifying the quark configurations in each colliding nucleons by (9) and (3)–(5) we calculate $G_{in}(s, b)$ for certain values of impact parameter b and then cross sections σ_{in} , σ_{el} and σ_{tot} . The values of adjusted parameters of the model, $x_{\max} = 0.64 fm$, $\sigma_{x,y} = 0.24 fm$ and $\sigma_z = 0.12 fm$, are chosen by comparison of calculated IOF with so called “BEL”-parametrization[3], (Fig. 4), and calculated inelastic cross sections with experimental ones, $\sigma_{in}(s)$, in pp and $\bar{p}p$ collisions at $\sqrt{s_{pp}} = 540 GeV$. Fig. 5 shows the result of calculation for pp total cross section at wide range of collision energies. One can see that the model with parameters fixed at one energy (540 GeV) describes the energetic behavior of σ_{tot} . The growth of cross sections with energy is due to the continuous tails of polarization fields around VQs not compensated by destructive interference with fields of two other VQs. With rising collision energy these tails result in the increasing effective size of hadronic matter distribution inside nucleons and correspondingly the increasing radius of interactions. The model gives for cross

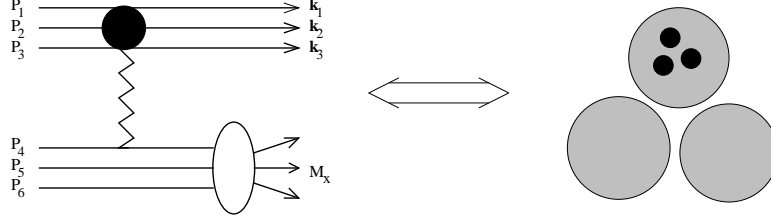


Figure 6: Correspondence between diagram and geometrical representation of single diffractive dissociation in $pp \rightarrow pX$ processes. Extended sizes of colliding nucleons are drawn on impact parameter plane: big grey circles are constituent quarks of dissociating nucleon, small black circles – (semi)bare quarks of the another nucleon.

sections linear logarithmic energy dependence and the curve deviates from data points at very high energies. The reason of this is that in our geometrical approach, ((12) – (16)), we didn't take into account the real part of scattering amplitude. At energies $\sqrt{s} < 30 \text{ GeV}$ calculated cross sections were corrected on contributions of Regge poles exchange by using Donnachie and Landshoff parametrization[7]: $\Delta\sigma_R^{tot} = 56.08s^{-0.4526}$

An oscillatory motion of VQs appearing as interplay between constituent and bare (current) quark configurations results in fluctuations of hadronic matter distribution inside colliding nucleons. The manifestation of these fluctuations is a variety of scattering processes, hard and soft, in particular, the process of single diffraction (SD). We select SD-events among inelastic $pp \rightarrow pX$ events with the criterion $1 - x_F < 0.1$, where $x_F = \frac{2}{\sqrt{s}}(k_1 + k_2 + k_3)$ (Fig. 6). Here k_1, k_2, k_3 are momenta of quarks forming the final state proton. As one can see, SD-events correspond to constituent quark configuration inside one colliding nucleon and (semi)bare quark configuration inside another one. Fig. 7 shows that calculated SD cross section slightly depends on energy; our calculation for LHC energy gives $\sigma_{SD}^{LHC}(pp) = 8.30 \pm 0.15 \text{ mb}$.

4 Discussions and Summary

Proposed dynamical model of hadron structure, SCQM, possesses some important features. Parameters of the model, maximal displacement of VQ, $x_{max} = 0.64 \text{ fm}$, and extension of quark and gluon condensate around VQs, $\sigma_{x,y} = 0.24 \text{ fm}$ and $\sigma_z = 0.12 \text{ fm}$ characterize extended sizes of hadron. Owing to non-compensated tails of vacuum condensates at outer sides of VQs and condition (18), the model describes the energy dependence of inelastic and total cross sections as a result of increasing effective sizes of colliding hadrons. On the other hand, there is no overlap of hadronic matter distributions in space between VQs of each interacting hadron even at very high energy collisions because destructive interference of their polarization fields reduces resulting hadronic matter

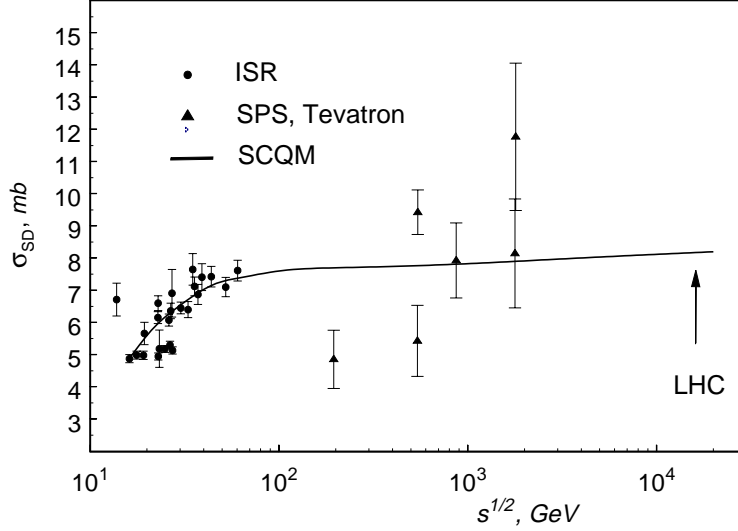


Figure 7: Single diffractive dissociation cross section for pp and $\bar{p}p$ - collisions; data points are compilations of experimental data taken from electronic data base HEPDATA[11].

at the center of quark system to zero value. So, the model keeps unitarity and does not need of inclusion of such a questionable effect as "antishadowing" [8]. According to our model diffraction dissociation is not shadowing effect of non-diffractive inelastic process – both compose inelastic process, they merely differ by configurations of quarks inside interacting hadrons.

Because of plane oscillations of VQs and flattened (perpendicular to the plane of oscillation) form of hadronic matter distributions nucleons are deformed, non-spherical objects. In paper [9], assuming that spin of VQs are perpendicular to the plane of oscillations, we showed that such a deformation of proton could manifest itself in total cross section differences between longitudinal and transversal polarization states in proton–proton collisions. Apparently experimental evidence of such a deformation are quadrupole transition amplitudes in $N \rightarrow \Delta$ electroproduction which are sensitive to quadrupole deformation of the nucleon[10].

Furthermore hadronic matter distribution inside hadrons and in turn the sizes of hadrons are fluctuating quantities. Fluctuations of extended sizes of nucleons allows one to understand why 'black disk' limit is not saturated in pp

and $\bar{p}p$ - collisions up to very high energies.

We must mention the paper[12] of S. Barshay with co-authors where they incorporated fluctuations in the eikonal into geometric picture for explaining of diffractive processes. There is a connection between eikonal and Inelastic Overlap Function used in our calculations of cross sections through the expression

$$G_{in}(b, s) = 1 - e^{-2Im\chi(b, s)}, \quad (19)$$

where $\chi(b, s)$ is eikonal. It is obvious that fluctuations of hadronic matter distributions caused by interplay between constituent and current quark configurations inside colliding hadrons lead to fluctuation of eikonal. In their approach the fluctuations of eikonal were controlled by phenomenological parameter, depending on energy. They predicted that single diffraction cross section increases reaching 14–15 mb at cms energies 20÷40 TeV then starts to decrease. Contrary to this prediction there is no apparent reason for any maximum, according to our approach, and this cross section increases steadily, very slightly up to asymptotic energies.

Our unified geometrical explanation of diffractive and nondiffractive processes could give an answer on long standing question: what is pomeron? Historically the concept of “pomeron”, starting from simple Regge pole with intercept $a_0 = 1$, transformed to a rather complicated object with relatively arbitrary features and smooth meaning. To produce rising cross sections it must have intercept such that $a_0 = 1 + \varepsilon$. The fact that the parameter ε is universal, independent of particles being scattered in hadronic and DIS interactions, could say us that the nature of the cross section growth is the same for all processes. Our interpretation of pomeron is geometrical one. Both diffractive and nondiffractive particle production emerge from disturbance (excitation) of overlapped continuous vacuum polarization fields (gluon and $\bar{q}q$ condensate) around valence quarks of colliding hadrons followed by fragmentation process. The type of interaction depends on quark configurations inside both colliding hadrons occurring at the instant of interaction and the value of impact parameter. So, what we used to call “Pomeron” in t - channel is solely continuum states in s - channel and we claim that Pomeron is unique in elastic, inelastic (diffractive and nondiffractive) and DIS.

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